

8-1-2010

A mobile threat to genome stability: The impact of non-LTR retrotransposons upon the human genome

Miriam K. Konkel
Louisiana State University

Mark A. Batzer
Louisiana State University

Follow this and additional works at: https://digitalcommons.lsu.edu/biosci_pubs

Recommended Citation

Konkel, M., & Batzer, M. (2010). A mobile threat to genome stability: The impact of non-LTR retrotransposons upon the human genome. *Seminars in Cancer Biology*, 20 (4), 211-221. <https://doi.org/10.1016/j.semcancer.2010.03.001>

This Article is brought to you for free and open access by the Department of Biological Sciences at LSU Digital Commons. It has been accepted for inclusion in Faculty Publications by an authorized administrator of LSU Digital Commons. For more information, please contact ir@lsu.edu.

Published in final edited form as:

Semin Cancer Biol. 2010 August ; 20(4): 211–221. doi:10.1016/j.semcancer.2010.03.001.

A mobile threat to genome stability: The impact of non-LTR retrotransposons upon the human genome

Miriam K. Konkel and Mark A. Batzer*

Department of Biological Sciences, Biological Computation and Visualization Center, Louisiana State University, 202 Life Sciences Building, Baton Rouge, Louisiana 70803, USA

Abstract

It is now commonly agreed that the human genome is not the stable entity originally presumed. Deletions, duplications, inversions, and insertions are common, and contribute significantly to genomic structural variations (SVs). Their collective impact generates much of the inter-individual genomic diversity observed among humans. Not only do these variations change the structure of the genome; they may also have functional implications, e.g. altered gene expression. Some SVs have been identified as the cause of genetic disorders, including cancer predisposition. Cancer cells are notorious for their genomic instability, and often show genomic rearrangements at the microscopic and submicroscopic level to which transposable elements (TEs) contribute. Here, we review the role of TEs in genome instability, with particular focus on non-LTR retrotransposons. Currently, three non-LTR retrotransposon families – long interspersed element 1 (L1), SVA (short interspersed element (SINE-R), variable number of tandem repeats (VNTR), and *Alu*), and *Alu* (a SINE) elements – mobilize in the human genome, and cause genomic instability through both insertion- and post-insertion-based mutagenesis. Due to the abundance and high sequence identity of TEs, they frequently mislead the homologous recombination repair pathway into non-allelic homologous recombination, causing deletions, duplications, and inversions. While less comprehensively studied, non-LTR retrotransposon insertions and TE-mediated rearrangements are probably more common in cancer cells than in healthy tissue. This may be at least partially attributed to the commonly seen global hypomethylation as well as general epigenetic dysfunction of cancer cells. Where possible, we provide examples that impact cancer predisposition and/or development.

Keywords

Retrotransposon; Non-Allelic homologous recombination; transposable element; genome instability; cancer

*Corresponding Author: Dr. Mark A. Batzer, Department of Biological Sciences, Biological Computation and Visualization Center, Louisiana State University, 202 Life Sciences Building, Baton Rouge, LA 70803 USA, Phone: (225) 578-7102; Fax: (225) 578-7113; mbatzer@lsu.edu.

Conflict of interest

The authors declare that there are no conflicts of interest.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

1. Introduction

Less than a decade ago, with the availability of the first human draft genome sequence, the human genome was considered to be a very stable entity [1]. However, with the identification of structural variations (SVs) as a major cause of inter-individual variation, it is now evident that the human genome is distinguished by a high inter-individual variability [2–6]. SVs are usually at the submicroscopic level and include insertions, deletions, duplications, translocations, and inversions. It is now commonly believed that SVs comprise more nucleotides than single nucleotide polymorphisms (SNPs) in the human genome [3]. Cancer cells are notorious for their genome instability. It is generally accepted that structural rearrangements at the microscopic level are common features of the genome of most human cancers. Recently the full impact of SVs, including those at the submicroscopic level in cancer cells, has become more apparent. Inherited rearrangements have also been associated with cancer predisposition and will be discussed in more detail in this review.

Transposable elements (TEs) are often involved in the genesis of SVs due to their inherent ability to mobilize, their abundance, and their high sequence identity. About half of the human genome is comprised of repetitive sequences, with TEs being the largest contributors [1,7]. The repeat content of the human genome is likely even higher, given that the decay of TEs over time makes the identification and characterization of ancestral TEs difficult if not impossible, and sequencing and assembly is less than perfect in repeat (and transposon)-rich regions [8,9]. Altogether, the impact of TEs onto the human genome has been underappreciated for some time; only recently are we beginning to comprehend the impact of TEs upon genome architecture and, consequently, onto the evolution of the human genome [10].

A recent comparative genomics study of two human genomes found that TEs are associated with ~10% of all SVs larger than 100 bp [11]. TEs impact genome integrity in several ways, including TE insertions and rearrangements. TEs are now commonly recognized in genetic diseases (reviewed in [7,12–16]). They have also been associated with cancer genesis; this is not unexpected, as a typical characteristic of cancer cells is their genomic instability. Here, we discuss the impact of TEs – in particular, non-LTR retrotransposons – upon the architecture of the genome; and review how and to what extent TEs have been associated with the genesis of cancer.

2. TE background

2.1 TE classification and activity

To understand the role of TEs within genome instability, it is important to review several key aspects of TE biology. For more detailed information we refer to other reviews (e.g. [7,12, 15,17,18]). TEs may be categorized by their mobilization mechanism into DNA transposons and retrotransposons. DNA transposons propagate via a cut-and-paste mechanism. While active in very early primate evolution, these elements have essentially ceased activity in the primate lineage approximately 37 million years ago [19]. In contrast, retrotransposons use an RNA intermediate; are reverse transcribed; and move within the genome through a copy-and-paste mechanism [15,20]. Retrotransposons are further subdivided into two groups on the basis of presence or absence of long terminal repeats (LTRs). The most prominent members of LTR-retrotransposons are endogenous retroviruses (ERVs), which comprise about 8% of the human genome [1]. There is very little (if any) evidence of ongoing ERV retrotransposition in humans [1,7,21]. Their potential role in tumorigenesis is subject to an ongoing debate and covered elsewhere (e.g., [22]). The other group encompasses non-LTR retrotransposons, and is discussed in more detail in this review.

2.2 Non-LTR retrotransposon biology

Three different families of non-LTR retrotransposons are actively mobilized in the human genome. These are long interspersed elements 1 (LINE1s, L1s); *Alu* elements (a short interspersed element, or SINE); and SVAs (named after their composite parts: SINE-R, VNTR (variable number of tandem repeats), and an *Alu*-like sequence) [1,7,12,15,23]. Their success is evident through the fact that non-LTR retrotransposons occupy about one third of the human genome, making them the most populous TE group in the human genome [1].

L1s are the only currently known autonomous (providing its own enzymatic machinery for retrotransposition) retrotransposons that are currently mobilizing within the human genome. They comprise about 17% (~500,000 copies) of the human genome with evidence of ongoing activity dating back roughly 160 million years [1]. A full-length L1 is about 6 kb in length and contains an internal Polymerase II promoter, two open reading frames (ORFs), and ends in a polyadenylation signal followed by a homopolymeric tract of Adenosines (also known as a polyA-tail; see Fig. 1) [24,25]. ORF1 protein is an RNA-binding protein [26] while ORF2 encodes a protein with both endonuclease and reverse transcriptase activity [27–29]. The majority of L1 insertions are retrotranspositionally incompetent due to variable truncation upon insertion and debilitating mutations [1]. Consequently, only about 80–100 retrotransposition competent L1s have been identified in the human genome [30]. Of those, a few (6–8) “hot” L1s appear to be responsible for the bulk of new insertions [30].

The human genome contains two actively mobilizing non-autonomous non-LTR retrotransposons: *Alu* elements (member of the SINE family) and SVAs. Non-autonomous elements are believed to rely on the enzymatic machinery of L1s for retrotransposition; e.g., as shown for *Alu* elements [31,32]. With more than 1,000,000 insertions, *Alu* elements are the most successful TE in the human genome by number [1]. This accomplishment is even more remarkable given that *Alu* elements are primate-specific and originated only about 65 million years ago [15]. *Alu* elements are heterodimers made of two non-identical monomers connected by an Adenosine-rich linker [15,33,34]. As shown in Fig. 1, an approximately 300 bp long *Alu* element contains an internal Polymerase III promoter at its 5' end, and ends in a polyA-tail.

SVA elements, which are altogether less well characterized than other non-LTR retrotransposons, represent the second group of currently mobilizing non-autonomous elements in the human genome. Similar to L1s, SVA insertions are often truncated and terminate in a polyadenylation signal followed by a polyA-tail (Fig. 1) [35,36]. It is now generally believed that SVA elements are transcribed by Polymerase II. However, an internal promoter has not been detected, and SVA transcription might – at least occasionally – take place through promoter activity in the vicinity of the SVA [35–37]. Due to their relatively recent origin (originating less than 25 million years ago), with ~3000 copies, SVA elements show the lowest retrotransposon density in the human genome [7,36].

Non-LTR retrotransposons are thought to typically insert into the human genome through a mechanism referred to as Target Primed Reverse Transcription (TPRT) [7,12,38,39]. During TPRT, the L1-derived endonuclease cuts the minus strand of the host DNA at a loosely recognized target site (5'-TTTT/AA-3') [28,40]. The polyA-tail of the non-LTR retrotransposon mRNA is proposed to bind to the free 3' end of the host DNA, and the mRNA is reverse transcribed by the reverse transcriptase encoded by L1 [41]. The next steps of second strand cleavage, second strand synthesis, and ligation are the subject of ongoing research. However, host repair systems have been implicated in the later stages of L1 retrotransposition [42–46]. A recent tissue culture based study further supports this, as proteins of the Non Homologous End-Joining (NHEJ) pathway were shown to be involved in L1 retrotransposition [47]. Due to a staggered break of the host DNA at the insertion site, the non-LTR

retrotransposon insertion is flanked by short stretches (usually between 6–20 bp) of identical host DNA, referred to as Target Site Duplications (TSD) [27,48].

3. Insertional mutagenesis

3.1 Potential impact upon the human genome

Inherited *de novo* TE insertions occur in the germline and/or during early embryogenesis [49–52]. *De novo* retrotransposon insertions account for about 0.3% of all human mutations [7]. The retrotransposition rate compatible with live birth varies greatly between the three retrotransposon families. *Alu* elements have the highest estimated retrotransposition rate, with ~1 in 20 live births, followed by L1 with about 1 in 200, and SVA with ~1 in 900 [7,11]. Consequently, non-LTR retrotransposons have a remarkable impact on genome plasticity and stability.

With few exceptions, retrotransposon insertions are neutral or in some cases even deleterious to the host [53]. Due to the unique properties of non-LTR retrotransposon insertions, an independent *de novo* insertion can be easily discriminated from a shared TE insertion that has been passed down over generations. These include random insertion site (apart from the loose recognition motif of the endonuclease cleavage site), unique TSDs, and identity of subfamily affiliation [15,54]. In the case of L1, the length of the insertion is yet another discriminating factor to discern shared from separate insertions [55]. Because the precise excision of non-LTR retrotransposons is exceedingly rare, the ancestral state is known to be the absence of the element; thus, TEs are generally homoplasmy free ([56], reviewed in [57]). Consequently, an insertion shared between two humans at exactly the same genomic location with identical TSDs is testimony to an inherited insertion and a common ancestor.

Deleterious insertions include the disruption of coding or regulatory sequences (reviewed in [12–14,16]). The coding sequence of genes can be disrupted when a non-LTR retrotransposon inserts into an exon, but also can be affected if the insertion occurs within an intron. While the impact of the latter event is often more difficult to demonstrate and may be overlooked, these insertions can potentially disrupt splice sites and cause exon skipping. It has also been implicated that an intronic TE insertion can alter the expression of a gene through introduction of alternative splice sites or polyadenylation signals [58–61]. Intronic insertions have also been associated with destabilization of the mRNA resulting in reduced expression [62]. In addition, insertions into the 5' and 3' prime region of genes can possibly alter their expression [63–65], reviewed in [66].

Alterations in gene expression increase the potential for altering equilibrium of regulatory networks, and thus augment susceptibility to certain diseases – including cancer.

3.2 Insertional mutagenesis and disease

All three currently actively mobilizing non-LTR retrotransposon families – L1, SVA, and *Alu* – have been identified as the causative agent of several genetic disorders. These include hemophilia, Alpert syndrome, familial hypercholesterolemia, and colon and breast cancer (reviewed in [7,12,13,16]). Several cancer predisposing mutations caused by retrotransposon insertions are shown in Table 1. Of all TE-causing genetic disorders identified to date, X-linked diseases are disproportionally over-represented compared to the autosomal diseases [7,12,62]. The X-chromosome is particularly enriched in inherited diseases caused by L1. The underlying reasons are the subject of ongoing debate (e.g. [7,12,62,67]). An ascertainment bias likely contributes (at least in part) to this finding, as the insertion on autosomes is commonly masked by the wild-type allele when standard PCR procedures are used. In particular, this is the case for longer TE insertions (L1 and SVA) where the wild-type allele has a much shorter

PCR amplicon. However, an insertional bias of L1 insertions toward the X-chromosome has also been reported [67].

The coding sequence of some genes has been disrupted more than once by independent non-LTR retrotransposon insertions [14]. An example is the BRCA2 gene, which is associated with breast/ovarian cancer susceptibility [68,69]. Moreover, some genes have been targeted twice at exactly the same location. The APC gene (associated with colon cancer predisposition) is an intriguing example, as one insertion was caused by an L1 and the other by an *Alu* element (Table 1) [14]. The fact that different genes have been identified with recurrent disease-causing retrotransposon insertions indicates that insertions do not solely occur by chance. Instead, this implies varying susceptibility to non-LTR retrotransposon insertions. The exact reasons for this finding are elusive. However, certain characteristics of these genes likely contribute to their predisposition for multiple retrotransposon insertions. For example, the presence of TEs and the nucleotide composition of introns prone to recurrent *de novo* TE insertions might play a pivotal role. The TE content of genes might be a contributing factor, as genes enriched in TE sequences harbor, on average, more sequences that resemble endonuclease cleavage sites, possibly increasing the proliferation of TEs.

For example, *Alu* elements have been shown to insert upstream of another element or within the polyA-tail of an existing element containing a less than perfect endonuclease cleavage site [70]. The TSD itself, created by classical TPRT, is a source for an additional endonuclease cleavage site. The spacer region (see Fig. 1) of *Alu* elements also closely resembles an endonuclease recognition site. Thus, one byproduct of *Alu* insertions is the creation of additional L1 endonuclease target sites suitable for the insertion of non-LTR retrotransposons. Also, recently inserted full-length L1s in particular contain several nucleotide sequences closely resembling endonuclease cleavage sites. However, TE density alone is likely not a sufficient explanation, as some genes with high TE density do not encounter recurrent *de novo* insertions. The methylation status and expression level of a gene may be other contributing factors as the DNA of genes that are actively transcribed may exist in more open chromatin structures that are more accessible to retrotransposition machinery and, therefore, may be more prone to *de novo* non-LTR insertions. The origin of a TE insertion can be reconstructed based on the geographical distribution of a TE insertion and its frequency within a population. In the case of cancer, several founder mutations involving *Alu* elements have been identified. For example, an *Alu* insertion into the BRCA2 gene has been identified in the Portuguese population [69]. The *Alu* insertion disrupts exon 3 which results in exon skipping. This skipping of exon 3 has also been found in individuals without the *Alu* insertion, and thus an association of the *Alu* insertion and cancer susceptibility has been questioned. However, a recent study convincingly linked the *Alu* founder mutation in the Portuguese population with cancer susceptibility [71].

3.3 Insertional mutagenesis of TEs in somatic cells

The investigation of TE retrotransposition activity in somatic cells at a comprehensive level was until recently out of reach. Advancements in detection technologies, in particular high-throughput sequencing approaches, are on the verge of changing this. While knowledge about somatic retrotransposition is still sparse, there is increasing evidence of ongoing L1 mobilization in healthy somatic tissues. For example, L1 protein has been identified in adult cells [72], and ongoing retrotransposition causing somatic mosaicism has been demonstrated in embryogenesis and within developing neuronal precursor cells [49–51]. *In vitro* assays using an L1 cassette with an adenovirus vector further indicate that L1 retrotransposition can occur in differentiated human primary cells in G1/S-arrested cells but not in G0-arrested cells [73]. Another study found that L1 retrotransposition under use of its endogenous L1 promoter requires cell divisions [74].

Furthermore, this research indicates that L1 retrotransposition occurs at (very) low levels in primary human fibroblast cell lines [74]. On the basis of these initial results, it appears likely that the retrotransposition frequency varies individually and also between different tissues. The TE mobilization rate in cancer cells is likely more pronounced in comparison to “normal” tissue due to the likely activation of L1s through demethylation of their promoters (see section 7). In addition, deleterious retrotransposon insertions might not underlie the same selection criteria in cancer cells compared to healthy tissue. For example, retrotransposon insertions that might typically result in apoptosis in normal cells may not cause cell death in cancer, given that the apoptosis pathway is often impaired in cancerous cells [75]. However, *in vitro* studies of human carcinoma cells suggest that apoptosis is positively correlated with the presence of retrotransposition-competent L1 [76]. Conceivably, the cell reaction to L1 reactivation is dosage-dependent.

3.4 TE insertions associated with deletion of host DNA

The deletion of host DNA associated with the *de novo* insertion of an L1 or *Alu* element was first demonstrated for L1 in tissue culture and confirmed by comparative genomics studies for both L1 and *Alu* insertions [77–82]. SVA elements have not been sufficiently studied in this context, but probably are equally involved in this mechanism. Two vastly different mechanisms, each with characteristic properties, have been identified causing deletions upon the insertion of non-LTR retrotransposons. These are TPRT-dependent insertion-mediated deletions and endonuclease-independent insertions [41,77,79–82]. The primary difference between the two mechanisms is the dependence on the L1 endonuclease.

3.4.1 Insertion-mediated deletions—Insertion-mediated deletions are endonuclease-dependent and are thought to make use of TPRT [41,77,79,80]. In these instances, an endonuclease cleavage site can be commonly identified at the insertion site. In addition, the 3' end of non-LTR retrotransposon insertions involved in insertion-mediated deletions (the insertion ends in a polyA-tail) is generally intact [77,79,80]. However, due to the deletion of the host sequence, TSDs are absent in these insertion-mediated events (see Fig. 2). While the precise insertion mechanism(s) of endonuclease-dependent TE insertion-mediated deletions remains elusive, two different mechanisms have been proposed depending on the size of the deleted host DNA [77]. Small deletions of only a few nucleotides could be caused through a nick of the top strand of the DNA to the right of the initial cleavage site resulting in a 5' overhang [77]. Larger deletions have been proposed to occur when a TE inserts downstream of a double strand break (DSB) [77].

A new line of evidence using *in vitro* assays indicates that disruption of the NHEJ pathway commonly results in deletion of host DNA upon endonuclease-dependent L1 insertion [47]. This part of the study was performed with zebrafish L1s in DT40 cells deficient in Ku70. Intriguingly, Ku70 is associated with the protection of DNA from exonucleolytic degradation [83]. This indicates that the host DNA of insertion-mediated deletions is not sufficiently protected from degradation at the endonuclease cleavage site. It is the subject of future studies to determine if this finding represents a typical *in vivo* mechanism of human L1 retrotransposition. However, it strongly supports the hypothesis of competition between the retrotransposon insertion event itself and an attempt by the host to repair the nascent insertion site [10,41].

A number of genetic disorders caused by TE insertion-mediated deletions have been identified (reviewed in [13,14]). *Alu* insertion-mediated deletion has been suggested as a mechanism for deletion in the APC gene, which is associated with colon cancer predisposition [14,84]. Somatic mutations involving this mechanism have not yet been identified. Altogether, the combination of host sequence deletion and a *de novo* retrotransposon insertion represents a large threat to

the integrity of the human genome and has a higher potential to be deleterious to the host than insertional mutagenesis alone.

3.4.2 Endonuclease-independent TE insertions—While the bulk of retrotransposon insertions are endonuclease-dependent and thus show the typical hallmarks of TPRT, a small fraction of endonuclease-independent L1 insertions has been observed in tissue culture cells deficient in NHEJ [78]. Although these insertions are also often associated with deletions of host DNA, these insertion events are not thought to be the products of the retrotransposition pathway; rather they occur by other mechanisms such as DSBs. Recently, comparative genomic studies have shown that endonuclease-independent L1 insertions are not tissue culture artifacts and also occur *in vivo* [81,82]. Up to 0.5% and 0.7% of L1 and *Alu* insertions respectively could be attributed to endonuclease-independent insertion mechanisms [7,81,82]. Apart from the deletion of host sequence and absence of a typical endonuclease-cleavage site, these non-LTR insertions are commonly 3' and 5' truncated and do not contain TSDs (Fig. 2) [78,81,82]. The average size of endonuclease-independent insertions is also in general smaller (e.g. 572 bp for L1 [81]) than that of recent classical non-LTR retrotransposon insertion events (e.g. 900 bp for L1 [1]) that are thought to have inserted using TPRT.

The deletion of host DNA in conjunction with the structure and mechanism of the TE insertion and the commonly found microhomology between the L1 insertion and the host DNA indicates that endonuclease-independent TE insertions are involved in DSB repair [78,81,82]. Hence, a very small fraction of TEs potentially contribute to cell integrity. A few endonuclease-independent L1 insertions have been identified in genetic disorders (reviewed in [62]). It remains an unanswered question if endonuclease-independent insertions occur only in the germline or if they are also common in somatic cells. While these insertions are probably involved in DNA repair and thus stabilizing, the deletion of host sequence can still be deleterious to the host and (for example) be associated with cancer predisposition. In cancer cells their contribution could be similar to other DSB repair mechanisms that can cause new oncogenes through fusion of two genes or disrupt tumor suppressor genes.

4. Inverted *Alu* elements cause genomic instability

On average, the human genome contains approximately one *Alu* insertion per every 3 kb [1]. However, *Alu* elements are not evenly distributed throughout the human genome [1]. Areas of higher than average *Alu* density have been particularly associated with genomic instability. The abundance of *Alu* insertions and high sequence homology between *Alu* elements (average 71%) [85] makes them targets for genome rearrangements (see section 5). Moreover, inverted *Alu* elements in close proximity to each other are less frequently identified in the human genome than *Alu* insertions in the same orientation [86,87]. This can only partially be attributed to insertional bias of *Alu* insertions in the same orientation [65,83]. Instead, inverted repeats likely represent hotspots of genomic instability, as seen in studies with yeast [86].

Inverted *Alu* elements that are closely spaced appear to build hairpin structures, which can cause DSBs of the DNA and excision of inverted *Alu* elements from the human genome [86,88]. Moreover, hairpin structures involving *Alu* elements appear to cause replication stalling and collapse of the replication fork, which can lead to DSBs and/or intra- or intermolecular template switch [88]. Apart from the distance of two inverted *Alu* insertions, the size of sequence identity between two *Alu* insertions seems to be an important contributing factor [87]. Despite their underrepresentation in the human genome, inverted repeats continue to cause genomic instability. Moreover, *de novo* *Alu* insertions can generate new inverted loci, which pose a potential threat for rearrangements in future human generations. Conceivably, these rearrangements can also occur in somatic cells and potentially contribute to cancer development.

5 TE-mediated recombination and genomic instability

5.1 Role of TE-mediated recombination in the human genome

Chromosomal structural variation is caused by two different general mechanisms: homologous recombination (HR) and NHEJ [89]. HR is highly conserved in a wide array of species, including prokaryotes and eukaryotes, suggesting that HR is a fundamental biological mechanism. Deficiencies involving HR have been associated with cancer development [90, 91]. While programmed HR occurs only once during chromosomal crossover in meiosis, HR is commonly involved in the repair of DSBs, preventing an individual from DNA damage (reviewed in [92]). For further information regarding DSB repair mechanisms, we refer to other recent reviews (e.g. [10,92]). If performed accurately, HR will repair the DNA without a trace. However, the process is often undermined by abundant and/or highly homologous sequences including TEs [10,93]. In these instances, two homologous sequences from different genomic locations recombine in a process called Non-Allelic Homologous Recombination (NAHR) and consequently cause deletions, duplications, or inversions, as illustrated in Fig. 3 [93–95].

In addition, TE-mediated NAHR can also result in translocations. It would seem reasonable to assume that given the abundance of TEs in the human genome, TE-mediated NAHR translocations would commonly occur by chance. TEs, in particular *Alu* elements, are often found in the vicinity or even within the breakage points of translocations [96]. However, few disease-associated translocations have been identified that clearly suggest the involvement of TE-mediated NAHR (e.g. [97]). This may be due to the requirements of the DSB repair pathways that cause translocations: NHEJ and Single Strand Annealing (SSA) [98]. SSA – which can create *Alu*-mediated NAHR translocations – is likely rarely utilized due to higher sequence homology requirements than usually found between two TEs [98,99]. Instead, NHEJ appears to be the main mechanism in the creation of translocations.

While insertional mutagenesis caused by TEs is occasionally deleterious to the host resulting in genetic disorders including cancer, post-insertional rearrangements of TEs pose altogether a far greater threat to the integrity of the genome [10]. While a TE insertion may disrupt the function of one gene, recombination between two TEs might result in the deletion of a functional region –including several genes, especially if two distant (not necessarily consecutive) TEs are involved. So far, most of our knowledge regarding TE-mediated recombination events is based on germline mutations, some of which cause genetic diseases (also referred to as genomic disorders). Rearrangements involving the germline can be *de novo* or inherited and passed on to future generations [100]. However, somatic structural variation also does occur [101]. TE-mediated NAHRs – both somatic and inherited – have been associated with cancer predisposition and development (e.g. [102–105]). Still, TE-mediated NAHR events are most likely underrepresented in studies involving cancer susceptibility, development, and progression as a consequence of detection challenges.

Comprehensive comparative genomics studies of the human and chimpanzee genomes have shown that L1 and *Alu* elements are commonly involved in TE-mediated recombination events causing deletions [93,94,106]. *Alu* elements are also often involved in NAHR-mediated duplications, as they have been found at chromosomal breakpoints of segmental duplications with a higher frequency (~27%) compared to the average *Alu* density (~10%) in the human genome [107]. Beyond genomic instability caused by *Alu*-mediated NAHRs that cause duplications, segmental duplications themselves represent hotspots for structural variation and genomic instability as they share a very high homology. As a result, they can lead to genetic disease and altered gene expression of genes located within these regions [58,92].

Analysis of the human genome using the chimpanzee genome as a reference indicates that deletions caused by *Alu*-mediated NAHR occur about 9 times more often (492 versus 55) than

L1-mediated NAHRs in the human genome [93,94]. The analysis of L1-mediated recombination deletions revealed also 18 chimeric L1s showing hallmarks of NHEJ, raising the number of recombination events to 73. In terms of frequency, L1 recombination plays a relatively minor role in the human genome. However, L1-mediated recombination events are significantly larger in size than *Alu*-mediated NAHRs (6132 bp versus 806 bp) [93,94]. L1 recombination-mediated deletions have deleted more DNA sequence from the human genome than the sum of all other TE deletion related events [94]. This includes DNA loss of *Alu* insertion-mediated deletions, L1 insertion-mediated deletions, and *Alu*-mediated NAHR deletions from the human genome over the last 5–6 million years [94]. Thus, L1 recombination-mediated deletions – even though less frequent – are a major contributor to genome instability. In addition, larger recombination events are more likely to involve greater disruption of functional genomic regions, making them more deleterious to the host. Consequently, these events are likely under significant negative selection, which commonly results in the loss of these events from the human population. These deletion events may commonly be so deleterious that affected individuals do not survive to birth. Indeed, to date only a few L1-mediated recombinations have been detected (reviewed in [14]).

5.2 TE-mediated NAHRs in human genetic disorders

TE-mediated NAHR events, in particular those involving *Alu* elements, have been identified in a variety of genetic disorders and play an important role in their genesis (reviewed in [13, 16]). Also, several *Alu*-mediated NAHRs with implications for cancer susceptibility have been identified; a subset is shown in Table 2. With few exceptions, NAHR-mediated deletions are more commonly detected than duplications. While in part this might be caused by a detection bias, as deletions are more easily identified compared to duplications, there is also evidence that overall deletions occur more often than duplications (reviewed in [92]). This may in part be explained by the intrachromatid NAHR mechanism which causes only deletions (see Fig. 3). Through advancements in detection methods for SVs, genomic rearrangements are now recognized in a number of genetic disorders. However, SVs are likely still severely underrepresented due to the required use of more complicated, lengthier, and resource consumptive methods to detect genomic rearrangements. The analysis of the *CDH1* gene – associated with hereditary diffuse gastric cancer (HDGC) – is an intriguing example. Up until 2009, only germline single nucleotide or small frameshift mutations were associated with HDGC [108,109]. Yet in individuals with HDGC, mutations were identified in only 30–50% of the cases. Oliveira and colleagues [108] have convincingly shown that some individuals with HDGC harbor structural variations including two *Alu*-mediated NAHRs that disrupt the *CDH1* gene. The identification of all mutations including structural variations in genes associated with cancer is of great importance for the identification of carriers, counseling, appropriate individualized screening and preventive measures. Counseling of breast cancer patients is another intriguing example, as a recent retrospective study found that close to 50% of breast cancer patients with *BRCA1* mutations eventually develop contra-lateral breast cancer [110].

5.3 Predisposition to TE-mediated NAHRs

It appears that some genes are more prone to TE-mediated NAHRs than others, as multiple recurrent independent recombination events have been identified in these genes [16]. For example, the *BRCA1* (and to a lesser extent *BRCA2*), *VHL*, *MLL1*, *MLH1*, and *MSH2* genes encountered recurrent *Alu*-mediated NAHRs (e.g. [102,111,112]). In some genes, 25% or more of cancer predisposing mutations in certain demographic populations are caused by *Alu*-mediated NAHRs (e.g. [102,113]). The overall density of *Alu* elements seems to be a contributing factor to recurrent *Alu*-mediated NAHRs as genes with higher than average *Alu* density in general show evidence of a higher *Alu*-mediated NAHR rate. Another factor could be the absence of epigenetic constraints such as CpG methylation and/or histone acetylation.

MLH1 and MSH2, both involved in the mismatch repair system, are two intriguing examples. Point mutations, small insertions and deletions, and genomic rearrangements within these genes are associated with hereditary non-polyposis colorectal cancer, the most common form of inherited colon cancer (e.g. [111,114]). Both genes have a higher than average *Alu* density within their intronic sequence (20% MLH1 and 40% MSH2 compared to 10% genome average) [111]. In the MSH2 gene ~3/4 of rearrangements are caused by *Alu*-mediated NAHRs [111]. In contrast, only about a fourth of the rearrangements of the MLH1 gene contained hallmarks of unequal *Alu* recombination [111]. The majority of the other events show characteristics of NHEJ often with involvement of TEs (in particular *Alu* elements). Another contributing factor to multiple independent *Alu*-mediated NAHRs is the age of the involved *Alu* insertions, as members of the youngest *Alu* subfamily, *AluY*, have been disproportionately detected in NAHRs relative to their density in the genome [93]. Occasionally, the same (often young) *Alu* element is involved in several independent NAHRs [102]. This is likely due to a higher homology of the *Alu* element, as younger insertions have on average accumulated fewer point mutations. This is further supported by a recent study that showed that *AluY* elements that are fixed in the human genome are associated with an increased local recombination rate [115].

The majority of TE-mediated rearrangements are sporadic and specific to the individual in whom the event was detected, and possibly also in immediate family members. However, some *Alu*-mediated NAHRs founder mutations have been identified in certain populations. For example, out of more than 60 reported BRCA1 rearrangements, the majority of which were caused by unequal recombination of *Alu* elements, six founder mutations have been identified [113,116]. One *Alu*-mediated NAHR event – identified in the Dutch population – accounts for about a quarter of all variations identified in the BRCA1 gene in this demographic population [113]. Due to this founder mutation, the Dutch population has to date the largest fraction of mutations caused by structural variation in the BRCA1 gene. Analysis of the breakage point at the DNA sequence level can discriminate between identical and independent rearrangements. Inherited genomic rearrangements share identical DNA breakage points. The occurrence of two separate identical NAHRs is extraordinarily unlikely. In addition, SNP and/or microsatellite information in the vicinity of the rearrangement can be used as further support for a shared or separate event.

Rearrangements in the MLL gene are in several ways intriguing. SVs involving this gene are commonly identified in acute myeloid leukemia (AML) [103,104,117]. Beside the recurrence of translocations in certain AML cancers, partial *Alu*-mediated NAHR duplications commonly occur within the coding sequence of this gene [103,117]. The most common in-frame duplication events create in-frame fusions of exons 11 or 12 upstream of exon 5 [103,117]. At the same time, partial deletions involving this region of the genome have not been identified [104]. Thus, it seems likely that another recombination mechanism is involved in the genesis of these partial duplications. Synthesis –dependent strand annealing (see [10]), a repair mechanism of DSBs in mammalian cells, could generate a partial duplication in the MLL1 gene. This mechanism was suggested for the creation of somatic tandem duplications in MYB, a transcription factor that can be associated with T-cell acute lymphoblastic leukemia (T-ALL) [118]. In addition, the MLL gene represents one of a few genes in which several independent somatic *Alu*-mediated NAHRs have been detected. While partial duplications show a high prevalence in patients with AML [103,117], these events have also been identified in hematopoietic cells of healthy blood donors [119]. More recently, it has been shown that suppression of the wild-type allele with expression of the MLL partial duplication allele contributes to the leukemic phenotype [120].

6. L1 induces double strand breaks

Another mechanism by which L1s potentially contribute to genome instability in their human host, is the observation that the L1 endonuclease creates far more DSBs than required for retrotransposition in mammalian cells [43]. To what extent these tissue culture observations will translate to human genomic instability remains elusive, as L1 expression under these experimental conditions was also far greater than under normal physiological conditions. It may not be possible to confirm or refute this mechanism *in vivo* because DSBs caused by L1 are indistinguishable from DSBs caused by other mechanisms [10,43]. Regardless, DSBs compromise DNA integrity, are highly recombinogenic, and exacerbate genomic instability.

7. Methylation status and retrotransposition

In various tumors studied, global demethylation with site-specific hypermethylation has been associated with cancer development and progression (reviewed in [121]). Hypomethylation varies considerably between different cancers, and in some tumor cells hypomethylation is associated with cancer development, while in others with progression [121]. The current model correlates global demethylation with an elevated mutation rate and chromosomal instability [122–124]. TEs including the promoters of L1 elements are often demethylated in cancer cells ([125,126], reviewed in [121]). The methylation of retrotransposons is believed to be a host defense mechanism in somatic cells against ongoing retrotransposition [127]. Indeed, for several cancer cell lines an increased L1 transcription rate has been detected in hypomethylated cancer cells [125,128]. One possible exception may be hepatocellular carcinoma cells, as these cells did not show evidence of this correlation [129].

Several points of evidence further support a correlation between hypomethylation and TE activation and increased recombination rates. The lack of regular *de novo* methylation of LTR and non-LTR retrotransposons through Dnmt3L (DNA methyltransferase 3-like) in non-dividing precursors of spermatogonial mouse stem cells resulted in high transcription levels of these TEs and meiotic failure in spermatocytes [130]. Hypomethylated thymic lymphomas in transgenic mice carrying a hypomorphic DNA methyltransferase Dnmt1 allele showed evidence of chromosomal instability [123]. Moreover, somatic retrotransposition of an Intracisternal A Particle, an endogenous retrovirus, into the Notch1 gene was detected in several lymphomas in mice, indicating an activation of endogenous retroviruses through hypomethylation [131]. Finally, a somatic *de novo* L1 insertion into the APC gene has been identified in a human colon tumor [132].

The demethylation of TE promoters (e.g. L1 and ERVs) has possible implications beyond the activation of TE retrotransposition. Through activation of potent TE promoters, transcription factor levels might be globally modified and/or the expression of genes might be altered in the vicinity of demethylated promoters [121]. Moreover, demethylation might result in the activation of the L1 antisense promoter that is also located within the 5' UTR of a full-length element and which in turn can create chimeric transcripts [133]. Cancer-specific chimeric transcripts derived from L1 antisense promoters have been recently detected [134]. Intriguingly, these transcripts were derived from fixed, older L1s that are likely no longer capable of retrotransposition [134].

9. Conclusions

We have discussed the known manifold roles of TEs with respect to genome instability. Among other things, we have shown that TEs are major contributors to genomic rearrangements. We are just beginning to understand the full impact of TEs upon the genome architecture. It is now recognized that TEs play a role in cancer predisposition, development, and progression. The comprehensive use of recently available technologies such as second-generation sequencing

and advanced computational algorithms will allow us to understand the role of TEs in the human genome more deeply. Moreover, it seems highly likely we will soon enter an era of personal genomics. Future projects will greatly increase our understanding of human inter-variability, hotspots of alteration in the human genome, and disease associations. Soon, medical diagnostics and treatment decisions will greatly rely on the analysis of the individual's genome. We are already witnessing the emergence of personalized cancer treatments. In addition, detailed analyses of single cells and/or different tissues are about to become possible for the first time. Using these advancements, we will likely discover a great deal of variation within individual humans. Cancer in particular seems a prime candidate for detailed structural variation studies, as genomic instability and dynamics in genome structure are typical characteristics of cancer cells. A fascinating era employing use of these rapidly evolving technologies lies ahead of us, along with the opportunity to deepen our understanding of TE biology and genome evolution.

Acknowledgments

We thank Jerilyn A. Walker, Thomas J. Meyer, George Cook, and Brygg Ullmer for their thoughtful advice during the preparation the manuscript. This work was supported by National Institutes of Health grants RO1 GM59290 and PO1 AG0022064 (M.A.B.).

Abbreviations

TE	Transposable element
SV	structural variation
ERV	endogenous retrovirus
ORF	open reading frame
UTR	untranslated region
LINE 1	L1, long interspersed element 1
SINE	short interspersed element
SVA	SINE-R—variable number of tandem repeats (VNTR)— <i>Alu</i>
TSD	target site duplication
NHEJ	non-homologous end-joining
SSA	single strand annealing
DSB	double strand break
HR	homologous recombination
NAHR	non-allelic homologous recombination
SNP	single nucleotide polymorphism
HDGC	hereditary diffuse gastric cancer
AML	acute myeloid leukemia
T-ALL	T-cell acute lymphoblastic leukemia
Dnmt3L	DNA methyltransferase 3-like

References

1. Lander ES, Linton LM, Birren B, Nusbaum C, Zody MC, Baldwin J, et al. Initial sequencing and analysis of the human genome. *Nature* 2001;409:860–921. [PubMed: 11237011]

2. Conrad DF, Pinto D, Redon R, Feuk L, Gokcumen O, Zhang Y, et al. Origins and functional impact of copy number variation in the human genome. *Nature*. 2009
3. Redon R, Ishikawa S, Fitch KR, Feuk L, Perry GH, Andrews TD, et al. Global variation in copy number in the human genome. *Nature* 2006;444:444–54. [PubMed: 17122850]
4. Sebat J, Lakshmi B, Troge J, Alexander J, Young J, Lundin P, et al. Large-scale copy number polymorphism in the human genome. *Science* 2004;305:525–8. [PubMed: 15273396]
5. Iafrate AJ, Feuk L, Rivera MN, Listewnik ML, Donahoe PK, Qi Y, et al. Detection of large-scale variation in the human genome. *Nat Genet* 2004;36:949–51. [PubMed: 15286789]
6. Kidd JM, Cooper GM, Donahue WF, Hayden HS, Sampas N, Graves T, et al. Mapping and sequencing of structural variation from eight human genomes. *Nature* 2008;453:56–64. [PubMed: 18451855]
7. Cordaux R, Batzer MA. The impact of retrotransposons on human genome evolution. *Nat Rev Genet* 2009;10:691–703. [PubMed: 19763152]
8. Smit AF. The origin of interspersed repeats in the human genome. *Curr Opin Genet Dev* 1996;6:743–8. [PubMed: 8994846]
9. Smit AF, Toth G, Riggs AD, Jurka J. Ancestral, mammalian-wide subfamilies of LINE-1 repetitive sequences. *J Mol Biol* 1995;246:401–17. [PubMed: 7877164]
10. Hedges DJ, Deininger PL. Inviting instability: Transposable elements, double-strand breaks, and the maintenance of genome integrity. *Mutat Res* 2007;616:46–59. [PubMed: 17157332]
11. Xing J, Zhang Y, Han K, Salem AH, Sen SK, Huff CD, et al. Mobile elements create structural variation: analysis of a complete human genome. *Genome Res* 2009;19:1516–26. [PubMed: 19439515]
12. Belancio VP, Hedges DJ, Deininger P. Mammalian non-LTR retrotransposons: for better or worse, in sickness and in health. *Genome Res* 2008;18:343–58. [PubMed: 18256243]
13. Callinan PA, Batzer MA. Retrotransposable elements and human disease. *Genome Dyn* 2006;1:104–15. [PubMed: 18724056]
14. Chen JM, Stenson PD, Cooper DN, Ferec C. A systematic analysis of LINE-1 endonuclease-dependent retrotranspositional events causing human genetic disease. *Hum Genet* 2005;117:411–27. [PubMed: 15983781]
15. Batzer MA, Deininger PL. Alu repeats and human genomic diversity. *Nat Rev Genet* 2002;3:370–9. [PubMed: 11988762]
16. Deininger PL, Batzer MA. Alu repeats and human disease. *Mol Genet Metab* 1999;67:183–93. [PubMed: 10381326]
17. Goodier JL, Kazazian HH Jr. Retrotransposons revisited: the restraint and rehabilitation of parasites. *Cell* 2008;135:23–35. [PubMed: 18854152]
18. Kazazian HH Jr. Mobile elements: drivers of genome evolution. *Science* 2004;303:1626–32. [PubMed: 15016989]
19. Pace JK 2nd, Feschotte C. The evolutionary history of human DNA transposons: evidence for intense activity in the primate lineage. *Genome Res* 2007;17:422–32. [PubMed: 17339369]
20. Ostertag EM, Kazazian HH Jr. Biology of mammalian L1 retrotransposons. *Annu Rev Genet* 2001;35:501–38. [PubMed: 11700292]
21. Mills RE, Bennett EA, Iskow RC, Devine SE. Which transposable elements are active in the human genome? *Trends Genet* 2007;23:183–91. [PubMed: 17331616]
22. Kurth R, Bannert N. Beneficial and detrimental effects of human endogenous retroviruses. *Int J Cancer* 2010;126:306–14. [PubMed: 19795446]
23. Bennett EA, Keller H, Mills RE, Schmidt S, Moran JV, Weichenrieder O, et al. Active Alu retrotransposons in the human genome. *Genome Res* 2008;18:1875–83. [PubMed: 18836035]
24. Babushok DV, Kazazian HH Jr. Progress in understanding the biology of the human mutagen LINE-1. *Hum Mutat* 2007;28:527–39. [PubMed: 17309057]
25. Skowronski J, Fanning TG, Singer MF. Unit-length line-1 transcripts in human teratocarcinoma cells. *Mol Cell Biol* 1988;8:1385–97. [PubMed: 2454389]
26. Martin SL, Branciforte D, Keller D, Bain DL. Trimeric structure for an essential protein in L1 retrotransposition. *Proc Natl Acad Sci U S A* 2003;100:13815–20. [PubMed: 14615577]

27. Feng Q, Moran JV, Kazazian HH Jr, Boeke JD. Human L1 retrotransposon encodes a conserved endonuclease required for retrotransposition. *Cell* 1996;87:905–16. [PubMed: 8945517]
28. Jurka J. Sequence patterns indicate an enzymatic involvement in integration of mammalian retroposons. *Proc Natl Acad Sci U S A* 1997;94:1872–7. [PubMed: 9050872]
29. Mathias SL, Scott AF, Kazazian HH Jr, Boeke JD, Gabriel A. Reverse transcriptase encoded by a human transposable element. *Science* 1991;254:1808–10. [PubMed: 1722352]
30. Brouha B, Schustak J, Badge RM, Lutz-Prigge S, Farley AH, Moran JV, et al. Hot L1s account for the bulk of retrotransposition in the human population. *Proc Natl Acad Sci U S A* 2003;100:5280–5. [PubMed: 12682288]
31. Dewannieux M, Esnault C, Heidmann T. LINE-mediated retrotransposition of marked Alu sequences. *Nat Genet* 2003;35:41–8. [PubMed: 12897783]
32. Wei W, Gilbert N, Ooi SL, Lawler JF, Ostertag EM, Kazazian HH, et al. Human L1 retrotransposition: cis preference versus trans complementation. *Mol Cell Biol* 2001;21:1429–39. [PubMed: 11158327]
33. Weiner AM, Deininger PL, Efstratiadis A. Nonviral retroposons: genes, pseudogenes, and transposable elements generated by the reverse flow of genetic information. *Annu Rev Biochem* 1986;55:631–61. [PubMed: 2427017]
34. Roy-Engel, AM.; Batzer, MA.; Deininger, P. *Encyclopedia of Life*. John Wiley & Sons, Ltd; 2008. Evolution of human retrosequences: Alu.
35. Ostertag EM, Goodier JL, Zhang Y, Kazazian HH Jr. SVA elements are nonautonomous retrotransposons that cause disease in humans. *Am J Hum Genet* 2003;73:1444–51. [PubMed: 14628287]
36. Wang H, Xing J, Grover D, Hedges DJ, Han K, Walker JA, et al. SVA elements: a hominid-specific retroposon family. *J Mol Biol* 2005;354:994–1007. [PubMed: 16288912]
37. Damert A, Raiz J, Horn AV, Lower J, Wang H, Xing J, et al. 5'-Transducing SVA retrotransposon groups spread efficiently throughout the human genome. *Genome Res* 2009;19:1992–2008. [PubMed: 19652014]
38. Cost GJ, Feng Q, Jacquier A, Boeke JD. Human L1 element target-primed reverse transcription in vitro. *EMBO J* 2002;21:5899–910. [PubMed: 12411507]
39. Luan DD, Eickbush TH. RNA template requirements for target DNA-primed reverse transcription by the R2 retrotransposable element. *Mol Cell Biol* 1995;15:3882–91. [PubMed: 7540721]
40. Cost GJ, Boeke JD. Targeting of human retrotransposon integration is directed by the specificity of the L1 endonuclease for regions of unusual DNA structure. *Biochemistry* 1998;37:18081–93. [PubMed: 9922177]
41. Symer DE, Connelly C, Szak ST, Caputo EM, Cost GJ, Parmigiani G, et al. Human L1 retrotransposition is associated with genetic instability in vivo. *Cell* 2002;110:327–38. [PubMed: 12176320]
42. Beauregard A, Curcio MJ, Belfort M. The take and give between retrotransposable elements and their hosts. *Annu Rev Genet* 2008;42:587–617. [PubMed: 18680436]
43. Gasior SL, Wakeman TP, Xu B, Deininger PL. The human LINE-1 retrotransposon creates DNA double-strand breaks. *J Mol Biol* 2006;357:1383–93. [PubMed: 16490214]
44. Gilbert N, Lutz S, Morrish TA, Moran JV. Multiple fates of L1 retrotransposition intermediates in cultured human cells. *Mol Cell Biol* 2005;25:7780–95. [PubMed: 16107723]
45. Ichianagi K, Nakajima R, Kajikawa M, Okada N. Novel retrotransposon analysis reveals multiple mobility pathways dictated by hosts. *Genome Res* 2007;17:33–41. [PubMed: 17151346]
46. Zingler N, Willhoeft U, Brose HP, Schoder V, Jahns T, Hanschmann KM, et al. Analysis of 5' junctions of human LINE-1 and Alu retrotransposons suggests an alternative model for 5'-end attachment requiring microhomology-mediated end-joining. *Genome Res* 2005;15:780–9. [PubMed: 15930490]
47. Suzuki J, Yamaguchi K, Kajikawa M, Ichianagi K, Adachi N, Koyama H, et al. Genetic evidence that the non-homologous end-joining repair pathway is involved in LINE retrotransposition. *PLoS Genet* 2009;5:e1000461. [PubMed: 19390601]
48. Szak ST, Pickeral OK, Makalowski W, Boguski MS, Landsman D, Boeke JD. Molecular archeology of L1 insertions in the human genome. *Genome Biol* 2002;3:research0052. [PubMed: 12372140]

49. Coufal NG, Garcia-Perez JL, Peng GE, Yeo GW, Mu Y, Lovci MT, et al. L1 retrotransposition in human neural progenitor cells. *Nature* 2009;460:1127–31. [PubMed: 19657334]
50. Muotri AR, Chu VT, Marchetto MC, Deng W, Moran JV, Gage FH. Somatic mosaicism in neuronal precursor cells mediated by L1 retrotransposition. *Nature* 2005;435:903–10. [PubMed: 15959507]
51. Kano H, Godoy I, Courtney C, Vetter MR, Gerton GL, Ostertag EM, et al. L1 retrotransposition occurs mainly in embryogenesis and creates somatic mosaicism. *Genes Dev* 2009;23:1303–12. [PubMed: 19487571]
52. van den Hurk JA, Meij IC, Seleme MC, Kano H, Nikopoulos K, Hoefsloot LH, et al. L1 retrotransposition can occur early in human embryonic development. *Hum Mol Genet* 2007;16:1587–92. [PubMed: 17483097]
53. Cordaux R, Lee J, Dinoso L, Batzer MA. Recently integrated Alu retrotransposons are essentially neutral residents of the human genome. *Gene* 2006;373:138–44. [PubMed: 16527433]
54. Ovchinnikov I, Troxel AB, Swergold GD. Genomic characterization of recent human LINE-1 insertions: evidence supporting random insertion. *Genome Res* 2001;11:2050–8. [PubMed: 11731495]
55. Myers JS, Vincent BJ, Udall H, Watkins WS, Morrish TA, Kilroy GE, et al. A comprehensive analysis of recently integrated human Ta L1 elements. *Am J Hum Genet* 2002;71:312–26. [PubMed: 12070800]
56. van de Lagemaat LN, Gagnier L, Medstrand P, Mager DL. Genomic deletions and precise removal of transposable elements mediated by short identical DNA segments in primates. *Genome Res* 2005;15:1243–9. [PubMed: 16140992]
57. Ray DA, Xing J, Salem AH, Batzer MA. SINEs of a nearly perfect character. *Syst Biol* 2006;55:928–35. [PubMed: 17345674]
58. Belancio VP, Deininger PL, Roy-Engel AM. LINE dancing in the human genome: transposable elements and disease. *Genome Med* 2009;1:97. [PubMed: 19863772]
59. Belancio VP, Roy-Engel AM, Deininger P. The impact of multiple splice sites in human L1 elements. *Gene* 2008;411:38–45. [PubMed: 18261861]
60. Han JS, Boeke JD. LINE-1 retrotransposons: modulators of quantity and quality of mammalian gene expression? *Bioessays* 2005;27:775–84. [PubMed: 16015595]
61. Perepelitsa-Belancio V, Deininger P. RNA truncation by premature polyadenylation attenuates human mobile element activity. *Nat Genet* 2003;35:363–6. [PubMed: 14625551]
62. Chen JM, Ferec C, Cooper DN. LINE-1 Endonuclease-Dependent Retrotranspositional Events Causing Human Genetic Disease: Mutation Detection Bias and Multiple Mechanisms of Target Gene Disruption. *J Biomed Biotechnol* 2006;2006:56182. [PubMed: 16877817]
63. Sobczak K, Krzyzosiak WJ. Structural determinants of BRCA1 translational regulation. *J Biol Chem* 2002;277:17349–58. [PubMed: 11877386]
64. Landry JR, Medstrand P, Mager DL. Repetitive elements in the 5' untranslated region of a human zinc-finger gene modulate transcription and translation efficiency. *Genomics* 2001;76:110–6. [PubMed: 11549323]
65. Chen LL, Carmichael GG. Gene regulation by SINES and inosines: biological consequences of A-to-I editing of Alu element inverted repeats. *Cell Cycle* 2008;7:3294–301. [PubMed: 18948735]
66. Hasler J, Samuelsson T, Strub K. Useful 'junk': Alu RNAs in the human transcriptome. *Cell Mol Life Sci* 2007;64:1793–800. [PubMed: 17514354]
67. Graham T, Boissinot S. The genomic distribution of I1 elements: the role of insertion bias and natural selection. *J Biomed Biotechnol* 2006;2006:75327. [PubMed: 16877820]
68. Miki Y, Katagiri T, Kasumi F, Yoshimoto T, Nakamura Y. Mutation analysis in the BRCA2 gene in primary breast cancers. *Nat Genet* 1996;13:245–7. [PubMed: 8640237]
69. Teugels E, De Brakeleer S, Goelen G, Lissens W, Sermijn E, De Greve J. De novo Alu element insertions targeted to a sequence common to the BRCA1 and BRCA2 genes. *Hum Mutat* 2005;26:284. [PubMed: 16088935]
70. El-Sawy M, Deininger P. Tandem insertions of Alu elements. *Cytogenet Genome Res* 2005;108:58–62. [PubMed: 15545716]

71. Peixoto A, Santos C, Rocha P, Pinheiro M, Principe S, Pereira D, et al. The c.156_157insAlu BRCA2 rearrangement accounts for more than one-fourth of deleterious BRCA mutations in northern/central Portugal. *Breast Cancer Res Treat* 2009;114:31–8. [PubMed: 18363094]
72. Ergun S, Buschmann C, Heukeshoven J, Dammann K, Schnieders F, Lauke H, et al. Cell type-specific expression of LINE-1 open reading frames 1 and 2 in fetal and adult human tissues. *J Biol Chem* 2004;279:27753–63. [PubMed: 15056671]
73. Kubo S, Seleme MC, Soifer HS, Perez JL, Moran JV, Kazazian HH Jr, et al. L1 retrotransposition in nondividing and primary human somatic cells. *Proc Natl Acad Sci U S A* 2006;103:8036–41. [PubMed: 16698926]
74. Shi X, Seluanov A, Gorbunova V. Cell divisions are required for L1 retrotransposition. *Mol Cell Biol* 2007;27:1264–70. [PubMed: 17145770]
75. Oren M. Decision making by p53: life, death and cancer. *Cell Death Differ* 2003;10:431–42. [PubMed: 12719720]
76. Belgnaoui SM, Gosden RG, Semmes OJ, Haoudi A. Human LINE-1 retrotransposon induces DNA damage and apoptosis in cancer cells. *Cancer Cell Int* 2006;6:13. [PubMed: 16670018]
77. Gilbert N, Lutz-Prigge S, Moran JV. Genomic deletions created upon LINE-1 retrotransposition. *Cell* 2002;110:315–25. [PubMed: 12176319]
78. Morrish TA, Gilbert N, Myers JS, Vincent BJ, Stamato TD, Taccioli GE, et al. DNA repair mediated by endonuclease-independent LINE-1 retrotransposition. *Nat Genet* 2002;31:159–65. [PubMed: 12006980]
79. Callinan PA, Wang J, Herke SW, Garber RK, Liang P, Batzer MA. Alu retrotransposition-mediated deletion. *J Mol Biol* 2005;348:791–800. [PubMed: 15843013]
80. Han K, Sen SK, Wang J, Callinan PA, Lee J, Cordaux R, et al. Genomic rearrangements by LINE-1 insertion-mediated deletion in the human and chimpanzee lineages. *Nucleic Acids Res* 2005;33:4040–52. [PubMed: 16034026]
81. Sen SK, Huang CT, Han K, Batzer MA. Endonuclease-independent insertion provides an alternative pathway for L1 retrotransposition in the human genome. *Nucleic Acids Res* 2007;35:3741–51. [PubMed: 17517773]
82. Srikanta D, Sen SK, Huang CT, Conlin EM, Rhodes RM, Batzer MA. An alternative pathway for Alu retrotransposition suggests a role in DNA double-strand break repair. *Genomics* 2009;93:205–12. [PubMed: 18951971]
83. Guirouilh-Barbat J, Huck S, Bertrand P, Pirzio L, Desmaze C, Sabatier L, et al. Impact of the KU80 pathway on NHEJ-induced genome rearrangements in mammalian cells. *Mol Cell* 2004;14:611–23. [PubMed: 15175156]
84. Su LK, Steinbach G, Sawyer JC, Hindi M, Ward PA, Lynch PM. Genomic rearrangements of the APC tumor-suppressor gene in familial adenomatous polyposis. *Hum Genet* 2000;106:101–7. [PubMed: 10982189]
85. Shen MR, Batzer MA, Deininger PL. Evolution of the master Alu gene(s). *J Mol Evol* 1991;33:311–20. [PubMed: 1774786]
86. Lobachev KS, Stenger JE, Kozyreva OG, Jurka J, Gordenin DA, Resnick MA. Inverted Alu repeats unstable in yeast are excluded from the human genome. *EMBO J* 2000;19:3822–30. [PubMed: 10899135]
87. Stenger JE, Lobachev KS, Gordenin D, Darden TA, Jurka J, Resnick MA. Biased distribution of inverted and direct Alus in the human genome: implications for insertion, exclusion, and genome stability. *Genome Res* 2001;11:12–27. [PubMed: 11156612]
88. Voineagu I, Narayanan V, Lobachev KS, Mirkin SM. Replication stalling at unstable inverted repeats: interplay between DNA hairpins and fork stabilizing proteins. *Proc Natl Acad Sci U S A* 2008;105:9936–41. [PubMed: 18632578]
89. van Gent DC, Hoeijmakers JH, Kanaar R. Chromosomal stability and the DNA double-stranded break connection. *Nat Rev Genet* 2001;2:196–206. [PubMed: 11256071]
90. Kennedy RD, D'Andrea AD. DNA repair pathways in clinical practice: lessons from pediatric cancer susceptibility syndromes. *J Clin Oncol* 2006;24:3799–808. [PubMed: 16896009]

91. Luo G, Santoro IM, McDaniel LD, Nishijima I, Mills M, Youssoufian H, et al. Cancer predisposition caused by elevated mitotic recombination in Bloom mice. *Nat Genet* 2000;26:424–9. [PubMed: 11101838]
92. Gu W, Zhang F, Lupski JR. Mechanisms for human genomic rearrangements. *Pathogenetics* 2008;1:4. [PubMed: 19014668]
93. Sen SK, Han K, Wang J, Lee J, Wang H, Callinan PA, et al. Human genomic deletions mediated by recombination between Alu elements. *Am J Hum Genet* 2006;79:41–53. [PubMed: 16773564]
94. Han K, Lee J, Meyer TJ, Remedios P, Goodwin L, Batzer MA. L1 recombination-associated deletions generate human genomic variation. *Proc Natl Acad Sci U S A* 2008;105:19366–71. [PubMed: 19036926]
95. Lee J, Han K, Meyer TJ, Kim HS, Batzer MA. Chromosomal inversions between human and chimpanzee lineages caused by retrotransposons. *PLoS One* 2008;3:e4047. [PubMed: 19112500]
96. Kolomietz E, Meyn MS, Pandita A, Squire JA. The role of Alu repeat clusters as mediators of recurrent chromosomal aberrations in tumors. *Genes Chromosomes Cancer* 2002;35:97–112. [PubMed: 12203773]
97. Onno M, Nakamura T, Hillova J, Hill M. Rearrangement of the human *trc* oncogene by homologous recombination between Alu repeats of nucleotide sequences from two different chromosomes. *Oncogene* 1992;7:2519–23. [PubMed: 1461655]
98. Elliott B, Richardson C, Jasin M. Chromosomal translocation mechanisms at intronic alu elements in mammalian cells. *Mol Cell* 2005;17:885–94. [PubMed: 15780943]
99. Weinstock DM, Richardson CA, Elliott B, Jasin M. Modeling oncogenic translocations: distinct roles for double-strand break repair pathways in translocation formation in mammalian cells. *DNA Repair (Amst)* 2006;5:1065–74. [PubMed: 16815104]
100. Lupski JR. Genomic rearrangements and sporadic disease. *Nat Genet* 2007;39:S43–7. [PubMed: 17597781]
101. Bruder CE, Piotrowski A, Gijsbers AA, Andersson R, Erickson S, de Stahl TD, et al. Phenotypically concordant and discordant monozygotic twins display different DNA copy-number-variation profiles. *Am J Hum Genet* 2008;82:763–71. [PubMed: 18304490]
102. Franke G, Bausch B, Hoffmann MM, Cybulla M, Wilhelm C, Kohlhasse J, et al. Alu-Alu recombination underlies the vast majority of large VHL germline deletions: Molecular characterization and genotype-phenotype correlations in VHL patients. *Hum Mutat* 2009;30:776–86. [PubMed: 19280651]
103. Schichman SA, Caligiuri MA, Strout MP, Carter SL, Gu Y, Canaani E, et al. ALL-1 tandem duplication in acute myeloid leukemia with a normal karyotype involves homologous recombination between Alu elements. *Cancer Res* 1994;54:4277–80. [PubMed: 8044771]
104. Strout MP, Marcucci G, Bloomfield CD, Caligiuri MA. The partial tandem duplication of ALL1 (MLL) is consistently generated by Alu-mediated homologous recombination in acute myeloid leukemia. *Proc Natl Acad Sci U S A* 1998;95:2390–5. [PubMed: 9482895]
105. Walsh T, Casadei S, Coats KH, Swisher E, Stray SM, Higgins J, et al. Spectrum of mutations in BRCA1, BRCA2, CHEK2, and TP53 in families at high risk of breast cancer. *JAMA* 2006;295:1379–88. [PubMed: 16551709]
106. Han K, Lee J, Meyer TJ, Wang J, Sen SK, Srikanta D, et al. Alu recombination-mediated structural deletions in the chimpanzee genome. *PLoS Genet* 2007;3:1939–49. [PubMed: 17953488]
107. Bailey JA, Liu G, Eichler EE. An Alu transposition model for the origin and expansion of human segmental duplications. *Am J Hum Genet* 2003;73:823–34. [PubMed: 14505274]
108. Oliveira C, Senz J, Kaurah P, Pinheiro H, Sanges R, Haegert A, et al. Germline CDH1 deletions in hereditary diffuse gastric cancer families. *Hum Mol Genet* 2009;18:1545–55. [PubMed: 19168852]
109. Oliveira C, Seruca R, Carneiro F. Genetics, pathology, and clinics of familial gastric cancer. *Int J Surg Pathol* 2006;14:21–33. [PubMed: 16501831]
110. Graeser MK, Engel C, Rhiem K, Gadzicki D, Bick U, Kast K, et al. Contralateral breast cancer risk in BRCA1 and BRCA2 mutation carriers. *J Clin Oncol* 2009;27:5887–92. [PubMed: 19858402]
111. Li L, McVety S, Younan R, Liang P, Du Sart D, Gordon PH, et al. Distinct patterns of germ-line deletions in MLH1 and MSH2: the implication of Alu repetitive element in the genetic etiology of Lynch syndrome (HNPCC). *Hum Mutat* 2006;27:388. [PubMed: 16541406]

112. Mazoyer S. Genomic rearrangements in the BRCA1 and BRCA2 genes. *Hum Mutat* 2005;25:415–22. [PubMed: 15832305]
113. Armaou S, Konstantopoulou I, Anagnostopoulos T, Razis E, Boukovinas I, Xenidis N, et al. Novel genomic rearrangements in the BRCA1 gene detected in Greek breast/ovarian cancer patients. *Eur J Cancer* 2007;43:443–53. [PubMed: 17174087]
114. Mitchell RJ, Farrington SM, Dunlop MG, Campbell H. Mismatch repair genes hMLH1 and hMSH2 and colorectal cancer: a HuGE review. *Am J Epidemiol* 2002;156:885–902. [PubMed: 12419761]
115. Witherspoon DJ, Watkins WS, Zhang Y, Xing J, Tolpinrud WL, Hedges DJ, et al. Alu repeats increase local recombination rates. *BMC Genomics* 2009;10:530. [PubMed: 19917129]
116. Petrij-Bosch A, Peelen T, van Vliet M, van Eijk R, Olmer R, Drusedau M, et al. BRCA1 genomic deletions are major founder mutations in Dutch breast cancer patients. *Nat Genet* 1997;17:341–5. [PubMed: 9354803]
117. Caligiuri MA, Strout MP, Schichman SA, Mrozek K, Arthur DC, Herzig GP, et al. Partial tandem duplication of ALL1 as a recurrent molecular defect in acute myeloid leukemia with trisomy 11. *Cancer Res* 1996;56:1418–25. [PubMed: 8640834]
118. O'Neil J, Tchinda J, Gutierrez A, Moreau L, Maser RS, Wong KK, et al. Alu elements mediate MYB gene tandem duplication in human T-ALL. *J Exp Med* 2007;204:3059–66. [PubMed: 18070937]
119. Schnittger S, Wormann B, Hiddemann W, Griesinger F. Partial tandem duplications of the MLL gene are detectable in peripheral blood and bone marrow of nearly all healthy donors. *Blood* 1998;92:1728–34. [PubMed: 9716602]
120. Whitman SP, Liu S, Vukosavljevic T, Rush LJ, Yu L, Liu C, et al. The MLL partial tandem duplication: evidence for recessive gain-of-function in acute myeloid leukemia identifies a novel patient subgroup for molecular-targeted therapy. *Blood* 2005;106:345–52. [PubMed: 15774615]
121. Wilson AS, Power BE, Molloy PL. DNA hypomethylation and human diseases. *Biochim Biophys Acta* 2007;1775:138–62. [PubMed: 17045745]
122. Eden A, Gaudet F, Waghmare A, Jaenisch R. Chromosomal instability and tumors promoted by DNA hypomethylation. *Science* 2003;300:455. [PubMed: 12702868]
123. Gaudet F, Hodgson JG, Eden A, Jackson-Grusby L, Dausman J, Gray JW, et al. Induction of tumors in mice by genomic hypomethylation. *Science* 2003;300:489–92. [PubMed: 12702876]
124. Roman-Gomez J, Jimenez-Velasco A, Agirre X, Castillejo JA, Navarro G, San Jose-Eneriz E, et al. Repetitive DNA hypomethylation in the advanced phase of chronic myeloid leukemia. *Leuk Res* 2008;32:487–90. [PubMed: 17765966]
125. Daskalos A, Nikolaidis G, Xinarianos G, Savvari P, Cassidy A, Zakopoulou R, et al. Hypomethylation of retrotransposable elements correlates with genomic instability in non-small cell lung cancer. *Int J Cancer* 2009;124:81–7. [PubMed: 18823011]
126. Suter CM, Martin DI, Ward RL. Hypomethylation of L1 retrotransposons in colorectal cancer and adjacent normal tissue. *Int J Colorectal Dis* 2004;19:95–101. [PubMed: 14534800]
127. Yoder JA, Walsh CP, Bestor TH. Cytosine methylation and the ecology of intragenomic parasites. *Trends Genet* 1997;13:335–40. [PubMed: 9260521]
128. Florl AR, Lower R, Schmitz-Drager BJ, Schulz WA. DNA methylation and expression of LINE-1 and HERV-K provirus sequences in urothelial and renal cell carcinomas. *Br J Cancer* 1999;80:1312–21. [PubMed: 10424731]
129. Lin CH, Hsieh SY, Sheen IS, Lee WC, Chen TC, Shyu WC, et al. Genome-wide hypomethylation in hepatocellular carcinogenesis. *Cancer Res* 2001;61:4238–43. [PubMed: 11358850]
130. Bourc'his D, Bestor TH. Meiotic catastrophe and retrotransposon reactivation in male germ cells lacking Dnmt3L. *Nature* 2004;431:96–9. [PubMed: 15318244]
131. Howard G, Eiges R, Gaudet F, Jaenisch R, Eden A. Activation and transposition of endogenous retroviral elements in hypomethylation induced tumors in mice. *Oncogene* 2008;27:404–8. [PubMed: 17621273]
132. Miki Y, Nishisho I, Horii A, Miyoshi Y, Utsunomiya J, Kinzler KW, et al. Disruption of the APC gene by a retrotransposal insertion of L1 sequence in a colon cancer. *Cancer Res* 1992;52:643–5. [PubMed: 1310068]

133. Speek M. Antisense promoter of human L1 retrotransposon drives transcription of adjacent cellular genes. *Mol Cell Biol* 2001;21:1973–85. [PubMed: 11238933]
134. Cruickshanks HA, Tufarelli C. Isolation of cancer-specific chimeric transcripts induced by hypomethylation of the LINE-1 antisense promoter. *Genomics* 2009;94:397–406. [PubMed: 19720139]
135. Halling KC, Lazzaro CR, Honchel R, Bufill JA, Powell SM, Arndt CA, et al. Hereditary desmoid disease in a family with a germline Alu I repeat mutation of the APC gene. *Hum Hered* 1999;49:97–102. [PubMed: 10077730]
136. Economou-Pachnis A, Tschlis PN. Insertion of an Alu SINE in the human homologue of the Mlvi-2 locus. *Nucleic Acids Res* 1985;13:8379–87. [PubMed: 3001638]
137. Wallace MR, Andersen LB, Saulino AM, Gregory PE, Glover TW, Collins FS. A de novo Alu insertion results in neurofibromatosis type 1. *Nature* 1991;353:864–6. [PubMed: 1719426]
138. Casarin A, Martella M, Polli R, Leonardi E, Anesi L, Murgia A. Molecular characterization of large deletions in the von Hippel-Lindau (VHL) gene by quantitative real-time PCR: the hypothesis of an alu-mediated mechanism underlying VHL gene rearrangements. *Mol Diagn Ther* 2006;10:243–9. [PubMed: 16884328]
139. Tournier I, Paillerets BB, Sobol H, Stoppa-Lyonnet D, Lidereau R, Barrois M, et al. Significant contribution of germline BRCA2 rearrangements in male breast cancer families. *Cancer Res* 2004;64:8143–7. [PubMed: 15548676]
140. Cybulski C, Wokolorczyk D, Huzarski T, Byrski T, Gronwald J, Gorski B, et al. A large germline deletion in the Chek2 kinase gene is associated with an increased risk of prostate cancer. *J Med Genet* 2006;43:863–6. [PubMed: 17085682]
141. Charbonnier F, Olschwang S, Wang Q, Boisson C, Martin C, Buisine MP, et al. MSH2 in contrast to MLH1 and MSH6 is frequently inactivated by exonic and promoter rearrangements in hereditary nonpolyposis colorectal cancer. *Cancer Res* 2002;62:848–53. [PubMed: 11830542]
142. van der Klift H, Wijnen J, Wagner A, Verkuilen P, Tops C, Otway R, et al. Molecular characterization of the spectrum of genomic deletions in the mismatch repair genes MSH2, MLH1, MSH6, and PMS2 responsible for hereditary nonpolyposis colorectal cancer (HNPCC). *Genes Chromosomes Cancer* 2005;44:123–38. [PubMed: 15942939]
143. Pistorius S, Gorgens H, Plaschke J, Hoehl R, Kruger S, Engel C, et al. Genomic rearrangements in MSH2, MLH1 or MSH6 are rare in HNPCC patients carrying point mutations. *Cancer Lett* 2007;248:89–95. [PubMed: 16837128]
144. Aissi-Ben Moussa S, Moussa A, Lovecchio T, Kourda N, Najjar T, Ben Jilani S, et al. Identification and characterization of a novel MLH1 genomic rearrangement as the cause of HNPCC in a Tunisian family: evidence for a homologous Alu-mediated recombination. *Fam Cancer* 2009;8:119–26. [PubMed: 18792805]
145. Thiffault I, Hamel N, Pal T, McVety S, Marcus VA, Farber D, et al. Germline truncating mutations in both MSH2 and BRCA2 in a single kindred. *Br J Cancer* 2004;90:483–91. [PubMed: 14735197]
146. Wagner A, Barrows A, Wijnen JT, van der Klift H, Franken PF, Verkuijen P, et al. Molecular analysis of hereditary nonpolyposis colorectal cancer in the United States: high mutation detection rate among clinically selected families and characterization of an American founder genomic deletion of the MSH2 gene. *Am J Hum Genet* 2003;72:1088–100. [PubMed: 12658575]
147. Froggatt NJ, Joyce JA, Evans DG, Lunt PW, Koch DJ, Ponder BJ, et al. MSH2 sequence variations and inherited colorectal cancer susceptibility. *Eur J Cancer* 1996;32A:178. [PubMed: 8695231]
148. Fukuuchi A, Nagamura Y, Yaguchi H, Ohkura N, Obara T, Tsukada T. A whole MEN1 gene deletion flanked by Alu repeats in a family with multiple endocrine neoplasia type 1. *Jpn J Clin Oncol* 2006;36:739–44. [PubMed: 17000701]
149. Rothberg PG, Ponnuru S, Baker D, Bradley JF, Freeman AI, Cibis GW, et al. A deletion polymorphism due to Alu-Alu recombination in intron 2 of the retinoblastoma gene: association with human gliomas. *Mol Carcinog* 1997;19:69–73. [PubMed: 9210953]
150. Hsieh SY, Chen WY, Yeh TS, Sheen IS, Huang SF. High-frequency Alu-mediated genomic recombination/deletion within the caspase-activated DNase gene in human hepatoma. *Oncogene* 2005;24:6584–9. [PubMed: 16007181]

151. Gervasini C, Venturin M, Orzan F, Friso A, Clementi M, Tenconi R, et al. Uncommon Alu-mediated NF1 microdeletion with a breakpoint inside the NF1 gene. *Genomics* 2005;85:273–9. [PubMed: 15676286]
152. Yap KP, Ang P, Lim IH, Ho GH, Lee AS. Detection of a novel Alu-mediated BRCA1 exon 13 duplication in Chinese breast cancer patients and implications for genetic testing. *Clin Genet* 2006;70:80–2. [PubMed: 16813611]

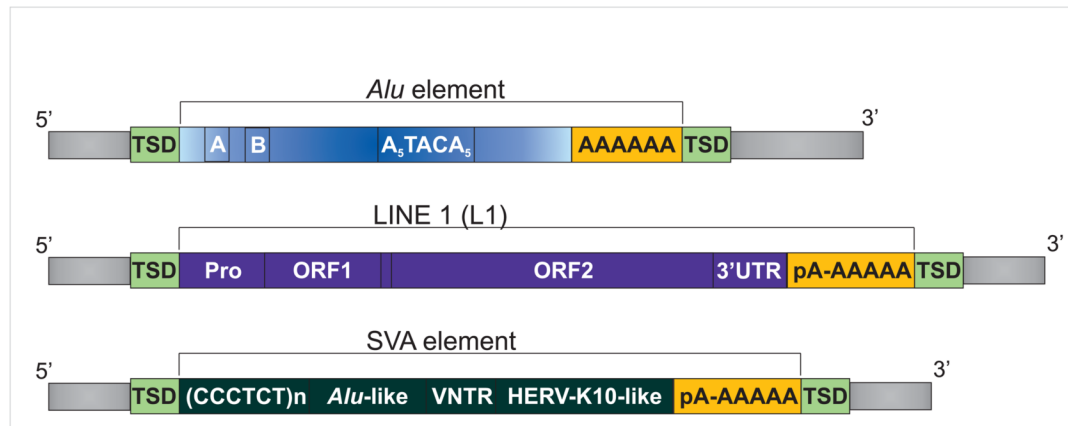


Fig. 1. Structure of non-LTR retrotransposons

Shown is structure of actively mobilizing retrotransposons in the human genome: an *Alu* element (blue), a full-length L1 (purple), and a full-length SVA (dark green). The non-LTR retrotransposons are not drawn to scale. All full-length non-LTR retrotransposons end in a homopolymeric tract of Adenosines (polyA-tail, yellow). SVA and L1 contain a polyadenylation signal (pA) immediately before the polyA-tail. Insertions are flanked by target site duplications (TSDs, green). *Alu* (blue): The A and B stand for the A and B boxes of the internal promoter. The left and right monomers are linked by a spacer sequence A₅TACA₅. L1 (purple): Pro stands for the internal Polymerase II promoter within the 5' untranslated region (UTR). A full-length L1 element contains two open reading frames (ORF1, ORF2). SVA (dark green): A full-length composite element contains from 5' to 3' a hexamer (CCCTCT), an *Alu*-homologous region of two antisense *Alu* fragments including other sequence of unknown origin, a variable number of tandem repeat (VNTR) region, and ends in a SINE region from parts of HERV-K10, an human endogenous retrovirus.

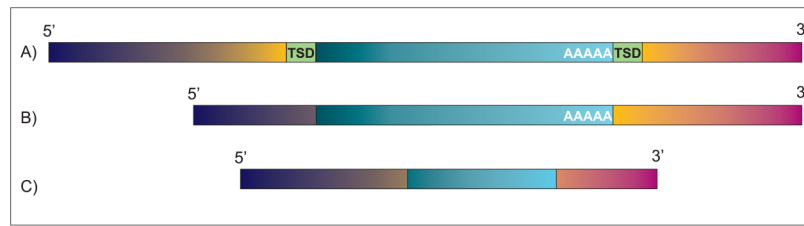


Fig. 2. Illustration of non-LTR retrotransposon insertion mechanisms

TSDs are shown in green; AAAAA stands for polyA-tail; A) Illustrates a typical non-LTR retrotransposon insertion. These insertions are thought to occur via TPRT. The insertion is 3' intact (contains a polyA-tail) and is flanked by TSDs. No host sequence is deleted. B) Shown are the typical hallmarks of an insertion-mediated deletion. The non-LTR retrotransposon is 3' intact, indicated by the polyA-tail. TSDs are absent; upstream (left) of the element, host DNA is deleted. C) Illustrated is an endonuclease-independent insertion with deletion of host DNA 3' and 5' of the insertion. However, deletions can be limited to 3' or 5' host DNA sequence. The non-LTR retrotransposon usually does not contain a polyA-tail and is not flanked by TSDs.

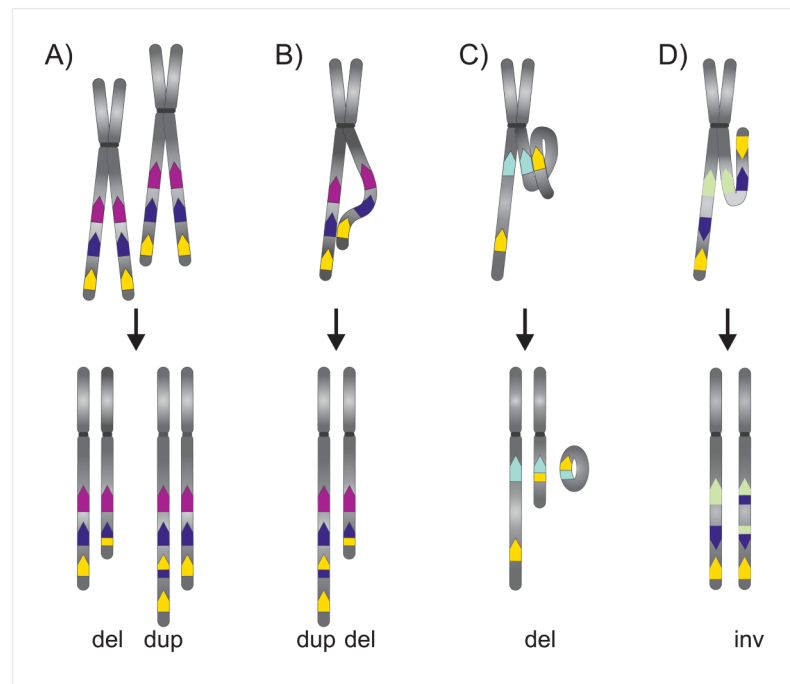


Fig. 3. Typical TE-mediated NAHR models

The colored arrows represent non-LTR retrotransposons of a given family; e.g. *Alu* elements. The tip of the arrow indicates the 3' end of the TE. TE-mediated NAHRs create a chimeric TE element (indicated by two different colors within element). The breakage point can be anywhere within the TE. While TE-mediated NAHRs are here shown for two adjacent elements, these events can occur between far removed TE elements in the geography of the chromosome. For A) to C) TEs are in the same orientation; for D) TEs involved in NAHR are inverted. Del stands for deletion, dup for duplication, and inv for inversion. A) Interchromosomal TE-mediated NAHR results in reciprocal deletion and duplication. (If two non-homologous chromosomes are involved a translocation can occur.). B) Intrachromosomal TE-mediated NAHR between two sister chromatids creates reciprocal deletion and duplication. C) Intrachromosomal, intrachromatid TE-mediated NAHR produces only a deletion. D) NAHR between two inverted TEs results in inversion of DNA between involved TEs.

Table 1

Selection of TE insertions associated with cancer predisposition.

Cancer-Associated Insertional Mutagenesis of Transposable Elements (TEs)				
Classical TPRT insertions				
Locus	Meaning	Cancer Association	TE	Distribution References
APC	Adenomatous Polyposis Coli gene	Colon Cancer	Alu	Germline [135]
APC			L1Ta	Somatic [132]
BRCA1	Breast Cancer 1 gene	Breast Cancer/Ovarian Cancer	Alu	Germline [69]
BRCA2	Breast Cancer 2 gene	Breast Cancer/Ovarian Cancer	Alu	Germline [68]
BRCA2			Alu	Germline [69]
MLV12	Moloney leukemia virus integration 2 homolog	Leukemia	Alu	Germline [136]
NF1	Neurofibromatosis 1 gene	Neurofibromatosis Type 1 ^a	Alu	Germline [137]
Insertion-mediated deletion				
Locus	Meaning	Cancer Association	TE	Distribution References
APC	Adenomatous Polyposis Coli gene	Cancer of the Colon	Alu	Germline [14,84]

^a ~10% of patients diagnosed with NF1 develop cancer

Table 2
Overview of cancer-associated *Alu* -mediated Non-Allelic Homologous Recombination (NAHR) events.

<i>Alu-Alu</i> Non-Allelic Homologous Recombination (NAHR) and Tumors					
Deletions					
Locus	Meaning	Tumor Association	Occurrence	# of events	References
VHL	von Hippel Lindau gene	von Hippel Lindau disease	Germline	Multiple ^a	[102,138]
BRCA1	Breast Cancer 1 gene	Breast/Ovarian Cancer	Germline	Multiple ^a	[105,113], reviewed in [112]
BRCA2	Breast Cancer 2 gene	Breast/Ovarian Cancer	Germline	Few ^b	[105,139]
CHEK	Checkpoint Kinase 2 gene	Breast Cancer	Germline	1	[105]
CHEK	Checkpoint Kinase 2 gene	Prostate Cancer	Germline	1	[140]
MLH1	MutL E. Coli Homolog 1 gene	Hereditary non polyposis colorectal cancer	Germline	Few ^c	[111,141–144]
MSH2	MutS E. coli Homolog 2 gene	Hereditary non polyposis colorectal cancer	Germline	Multiple ^a	[111,142,145–147]
MEN1	Multiple Endocrine Neoplasia Type 1 gene	Multiple Endocrine Neoplasia Type 1	Germline	1	[148]
CDH1	Cadherin 1 gene	Hereditary diffuse gastric cancer	Germline	Few ^c	[108]
RB	Retinoblastoma gene	Association with glioma	Germline	1	[149]
CAD	Caspase activated DNase gene	Hepatoma	Somatic	Recurrent ^{d?}	[150]
NF1	Neurofibromatosis 1 gene	Neurofibromatosis Type 1	Germline	1	[151]
Duplications					
Locus	Meaning	Tumor Association	Occurrence	# of events	References
MLL1	Myeloid/Lymphoid Mixed Lineage Leukemia gene	Acute myeloid leukemia (AML)	Somatic	Recurrent ^{d, d}	[103,104,119]
MYB	Transcription Factor	T-Acute Lymphoblastic Leukemia	Somatic	Recurrent ^{d?}	[118] [105,152], reviewed in
BRCA1	Breast Cancer 1 gene	Breast Cancer/Ovarian Cancer	Germline	Few ^c	[112]
BRCA2	Breast Cancer 2 gene		Germline	1	[105]
Translocations					
Locus	Meaning	Tumor Association	Occurrence	# of events	References
EWSR1-ETV6	wing Sarcoma Breakpoint Region 1 - ETS Variant gene	Ewing Sarcoma	Somatic	Recurrent ^{d?}	[97]

Number

^aMore than 10

^b More than 1 and less 10

^c Commonly detected

^d Also detected in healthy blood donors